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North Atlantic Multidecadal SST Oscillation: External forcing versus internal variability

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ABSTRACT

The Atlantic Multi-decadal Oscillation (AMO) depicts the swings of North Atlantic basin-wide sea surface temperature (SST) between warm and cold phases on a multi-decadal time scale. The 20th Century instrumental record indicates a relative cold period in the beginning of the 20th Century, a warm period in the 1940s and 50s, another cold period in the 1970s and 80s, followed by the recent warming period. These multi-decadal temperature swings coincide with an upward warming trend throughout the 20th Century. One of the central questions concerning these changes is whether they were caused by human activities, including aerosols and greenhouse gas forcing, or whether they reflect some combination between natural factors and human activity. Using both observations and CMIP3 model simulations, we argue that the overall changes are due to the combination of natural multidecadal variability and anthropogenic forcing. We also examine the regional surface temperature, precipitation, and atmospheric circulation features associated with the externally forced and internal North Atlantic SST multidecadal variability using both 20th Century observations and CMIP3 model simulations of the 20th, 21st, and pre-industrial forcing.

1. Introduction

The Atlantic Multidecadal Oscillation (AMO) represents a basin scale mode of variability in North Atlantic sea surface temperature (SST). The instrumental record is not long enough to determine if the phenomenon is truly oscillatory and this is why it is sometimes referred to as Atlantic Multidecadal Variability (AMV). However, using the instrumental records of the past 130 years, the “period” of the AMO is estimated to be 60–80 years (e.g., Schlesinger and Ramankutty, 1994). Reconstructions of the AMO based on paleoproxy suggest that the AMO period varies across a range of scales (Delworth and Mann, 2000; Gray et al., 2004; Knudsen et al., 2011).

The complexity in understanding the mechanisms and impacts of the observed AMO stems, in part, from its concurrence with the century-long, generally upward trend in North Atlantic SST, a trend that is possibly associated with the increase in global surface temperature attributed to anthropogenic forcing. By inferring the forced climate response using the ensemble mean Coupled Model Intercomparison Project phase 3 (CMIP3) models, Knight (2009) concluded that the observed AMO is inconsistent with the notion that it is a forced climate response, thus supporting the existence of an unforced component of the AMO. Ting et al. (2009) used the CMIP3's multi-model/multi-ensemble 20th Century simulations to estimate the radiatively forced North Atlantic SST trend and confirmed that the multi-decadal SST variability over the North Atlantic in 20th Century observations is well outside of the range of forced variability, consistent with the results of Knight (2009). Ting et al (2009) have further shown that the spatial structures of the forced and internal North Atlantic SST variability patterns are distinctly different from each other and each tied to unique worldwide precipitation anomalies. A more recent study by DelSole et al. (2010) argues that there exists a global pattern of internal multidecadal variability, separable from the anthropogenic signal and centered in the North Atlantic and North Pacific and that it contributed significantly to the global warming trend of the recent decades (1977–2008). This further emphasizes the necessity to separate between and accurately account for the forced and internal SST patterns of variability in the North Atlantic. Ting et al. (2011) examined further the robust patterns of the AMO in observations and CMIP3 simulations with various greenhouse and aerosol forcing scenarios, from pre-industrial to 21st Century A1b scenario, and concluded that the AMO is a mode of the coupled ocean–atmosphere system that is independent of external radiative forcing.

While the work discussed above advocates a role for unique internal mechanisms in creating the AMO, others have advocated the dominance of external forcing, at least as far as the 20th century variability is concerned. Mann and Emmanuel (2006), who focused on the tropical Atlantic sector, raised the possibility that the multi-decadal, Atlantic-centered SST variability in observations is entirely radiatively forced by a combination of greenhouse gas warming and cooling caused by industrial and volcanic aerosols. A recent study (Booth et al., 2012), using the Hadley Center Global Environmental Model version 2 — Earth System (HadGEM2-ES) with and without natural and anthropogenic aerosol forcing, argued that the 20th Century North Atlantic SST

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fluctuations are primarily forced by the direct and indirect aerosol radiative effects, contrary to the many previous studies that emphasize the role of internal ocean–atmosphere processes. Zhang et al. (2013) disputed the Booth et al. (2012) results by comparing a broad spectrum of observed and HadGEM2-ES model-simulated variables in addition to SST, and concluded that while the SST signal in the HadGEM2-ES results does indicate a large contribution of aerosols to 20th century AMO, there are large discrepancies between this simulation and observations resulting from the excessively strong and unrealistic aerosol indirect effects in that model. The issue of the role of aerosols in forcing the observed AMO thus remains an open question, one that will not be directly addressed in the current study. It should be emphasized however, that the analysis method used in this study, described in more details below, does take into account aerosol forcing as represented by pooling all models that participated in CMIP3.

This study extends that of Ting et al. (2009) and examines the relevant circulation and precipitation patterns and their seasonality associated with the forced and natural North Atlantic SST variability using both observations and CMIP3 models. The focus is on those features that are potentially relevant for fishery and coastal ecosystems such as the sea level pressure patterns, surface wind, and precipitation. The central issues are whether the forced and internal variability are separable, and if so, how do they differ in both spatial and temporal characteristics of their climate impacts.

2. Data and methods

The observed sea surface temperature (SST) used in this study is from the Goddard Institute for Space Studies (GISS) analysis of global surface temperature change (Hansen et al., 2010), which uses the HadISST1 (Rayner et al., 2003) from 1880 to 1981 and satellite measurements of SST from 1982 to the present (OISST.v2) (Reynolds et al., 2002). The global land precipitation and surface air temperature were taken from the UEA CRU TS2p1 monthly datasets with 0.5° × 0.5° resolutions (Mitchell and Jones, 2005).

The sea level pressure (SLP), surface wind, and 500 hpa geopotential height for observations are taken from the 20th Century reanalysis project (Compo et al., 20011) for the entire 20th Century.

In addition to the above observational datasets, we use outputs from the coupled ocean–atmosphere models used in the fourth assessment report of the Intergovernmental Panel on Climate Change (IPCC AR4) and the Climate Model Intercomparison Project phase 3 (CMIP3) organized by the World Climate Research Program (WCRP). A list of models and their corresponding ensemble members/length of integrations used in this study are shown in Table 1. We used four different types of simulations from CMIP3, the 20th Century forcing runs, which are forced with the observed solar, greenhouse gas and aerosol forcing during the 20th Century, the 21st Century A1B scenario runs, which is forced with the projected greenhouse gases and aerosol forcing for the 21st Century according to the A1B scenario, the 1%/year CO2 increasing experiment, which applies a gradual increase in greenhouse gas concentration but no aerosol forcing, and the pre-industrial run that has the fixed amount of CO2 at the pre-industrial level. A total of 23 models and 75 (54) ensemble members were used for the 20th (21st) Century simulations, while 20 models were available and used for the 1%/year and pre-industrial simulations. In the cases of the 20th, 21st Century simulations where the same model is used to generate multiple integrations, the radiative forcing remains the same for all ensemble members, but the initial condition differs slightly, allowing the integrations to deviate from each other due to internal atmospheric and oceanic variability, which by definition is temporally uncorrelated between ensemble members. Thus when averaged across the ensemble members, internal variability will be significantly reduced and the forced signal can be closely estimated from the ensemble average.

Following previous studies (Ting et al., 2009, 2011), the signal-to-noise ratio maximizing empirical orthogonal function analysis (S/N EOF) was used in this study to better extract the radiatively forced signal from the CMIP3 multi-model ensembles. The S/N EOF analysis entails a procedure that pre-whitens the raw model output data by first estimating the internal climate "noise" patterns from EOFs of the pre-industrial integrations (Allen and Smith, 1997). This pre-whitening procedure helps remove the internal variability that may be left in the multi-model ensemble average due to insufficient sampling and thus better extracts the forced patterns due to the common forcing applied in all model experiments.

Table 1
Summary of CMIP3 models and corresponding ensemble members (or years of integration) used in the paper.

Models	20th Century	21st Century (A1b)	1%/year CO2	Pre-industrial (yrs)
BCCR BCM2.0	1	1	1	250
CCCMA CGCM3.1	5	5	1	601
CCCMA CGCM3.1 T63	1	1	0	350
CNRM CM3	1	1	1	300
CSIRO MK3.0	3	1	1	380
CSIRO MK3.5	3	1	1	600
GFDL CM2.0	3	1	1	500
GFDL CM2.1	5	1	1	500
GISS AOM	2	2	0	251
GISS EH	5	3	1	0
GISS ER	9	5	0	500
INGV ECHAM4	1	1	1	0
INMCM3.0	1	1	1	330
IPSL CM4	1	1	1	500
MIROC3.2 HIRES	1	1	1	0
MIROC3.2 MEDRES	3	3	1	500
MIUB ECHO G	5	3	1	341
MPI ECHAM5	4	4	1	506
MRI CGCM2.3	5	5	1	350
NCAR CCSM3.0	8	7	1	500
NCAR PCM1	4	4	1	589
UKMO HADCM3	2	1	1	342
UKMO HADGEM1	2	1	1	240
ALL	75	54	20	20

3. Forced North Atlantic SST Variability

The observed annual mean North Atlantic SST index, which is the North Atlantic basin-wide average SST from the equator to 60ºN, is plotted in Fig. 1. A Butterworth low-pass filter with a cutoff frequency of 10 years was applied to the annual mean observations and is shown in red in the same figure but no other detrending procedure was used. In addition to residual interannual fluctuations, the index displays a large amplitude swing on multi-decadal time scales superimposed on a general upward trend throughout the record. Fig. 1b shows a tropical Atlantic SST index: SST averaged over the so-called Main Development Region (MDR, 6–18 N, 20–60 W) for the hurricane season (August, September and October). Are multidecadal fluctuations and trends in Fig. 1 forced responses to external forcing, i.e., anthropogenic and/or natural radiative forcing, or a manifestation of the internal ocean–atmosphere variability on multidecadal time scales? Given that the instrumental record is rather short with respect to the time scale of the fluctuation and the uncertainty in the radiative forcing during the 20th Century, one cannot conclusively state that there is a naturally occurring multi-decadal oscillation underlying the general warming trend. To address this question, we used climate model simulations in the 20th and 21st Centuries to help distinguish between the forced and natural components of the multidecadal SST variability in this study.

The S/N EOF analysis was first applied to annual mean low-pass (Butterworth filter with 10 year cutoff frequency) filtered North Atlantic SST (0°–60°N) using outputs from the multi-model, multi-ensemble members of the CMIP3 simulations of the 20th and 21st centuries. There were 23 models with a total of 75 multi-model